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16. ABSTRACT

A plug flow, O_2-activated sludge process was operated with alum addition to remove phosphorus and with lime addition to prevent the process pH from decreasing below 6.4. The O_2 reactor was operated at F/M ratios between 0.18 to 0.24 gm of BOD_5/gm of MLVSS/day in a typical co-current O_2-liquid contacting system. The alum dosages for the five steady-state operating periods increased from 84 mg/1 to 184 mg/1 was used to maintain the process pH at 6.4. The pollutant removals from the primary effluent ranged from 82 to 92% for BOD_5 (7.4 to 19 mg/1 of residual BOD_5) and from 54 to 86% for phosphorus (1.05 to 3.26 mg/1 of residual P). The optimum P removal occurred at a 1.8 to 1 average Al/P mole ratio with an average total residual P of 1.05 mg/1.

In a second study, the O_2 process was operated in a step-feed configuration consisting of a sludge oxygenation stage followed by three stages of oxygen aeration with equal portions of the primary effluent fed to each stage. In typical operation, the process with a F/M ratio of 0.23 exhibited a MLSS concentration profile in the four stages of 10,700 mg/1; 7,060 mg/1; 5,020 mg/1; and 4,150 mg/1. The step configuration clearly reduced the solids loading to the clarifier and provided an average MLSS of more than 6,500 mg/1. The step operation produced excellent BOD_5 removals (89% from primary). The O_2 usage in the step configuration was significantly less than the 90% typically achieved in co-current contacting.

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ALUM ADDITION AND STEP-FEED STUDIES IN OXYGEN-ACTIVATED SLUDGE

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The use of pure oxygen in the activated sludge process for removal of organic pollutants from wastewater and thus from the aqueous environment is being employed in an increasing number of treatment plants. This work describes firstly the use of mineral (alum) addition within the oxygen-activated sludge process to increase the removal of the phosphorus nutrients from the wastewater and secondly, an alternate process configuration for contacting the oxygen and the wastewater.

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Director
Municipal Environmental Research Laboratory

ABSTRACT

A plug flow, O_2-activated sludge process was operated with alum addition to remove phosphorus and with lime addition to prevent the process pH from decreasing below 6.4. The O_2 reactor was operated at F/M ratios between 0.18 to 0.24 gm of BOD_5/gm of MLVSS/day with the SRT varying from 4.7 to 6.0 days in a typical co-current O_2-liquid contacting system.

The average alum ($Al_2(SO_4)_3 \cdot 14\ H_2O$) dosages for the five steady-state operating periods increased from 84 mg/l to 184 mg/l with the 'l/P weight ratios increasing from 1.1 to 2.66. The amount of lime required to maintain the process pH at 6.4 or above varied from 15 mg/l to 58 mg/l as CaO. The lime demand was related to both the alum addition and to partial nitrification occurring in the oxygen reactor.

The pollutant removals from the primary effluent ranged from 82 to 92% for BOD_5 (7.4 to 19 mg/l of residual BOD_5), from 52 to 84% for suspended solids (17 to 56 mg/l of residual SS), and from 54 to 86% for phosphorus (1.05 to 3.26 mg/l of residual P). The optimum P removal occurred at a 1.8 to 1 average Al/P ratio with an average total residual P of 1.05 mg/l.

In a second study, the O_2 process was operated in a step-feed configuration consisting of a sludge oxygenation stage followed by three stages of oxygen aeration with equal portions of the primary effluent fed to each stage. In typical operation, the process with a F/M ratio of 0.23 exhibited a MLSS concentration profile in the four stages of 10,700 mg/l; 7,060 mg/l; 5,020 mg/l; and 4,150 mg/l. The step configuration clearly reduced the solids loading to the clarifier and provided an average process MLSS of more than 6,500 mg/l.

The step operation produced excellent BOD_5 removals (89% from the primary effluent) with an effluent BOD_5 of 10 mg/l and a soluble (filtered) effluent BOD_5 of less than 3 mg/l. The COD and suspended solids residual averaged 43 mg/l and 23 mg/l, respectively.

Oxygen balances, based upon inlet and outlet O_2 measurements and alternately upon O_2 uptake rates and upon the amount of O_2 in the outlet gas, revealed an O_2 usage of approximately 50%. The O_2 usage in the step configuration was significantly less than the 90% typically achieved in co-current contacting.

This report was submitted in partial fulfillment of Contract No. 68-01-0162 by the government of the District of Columbia, Department of Environmental Services under the sponsorship of the U.S. Environmental Protection Agency. This report covers experimental work conducted during the period October 1972-October 1973.

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SECTION 1

INTRODUCTION

The oxygen-activated sludge process with more than 90% utilization of oxygen has developed in recent years into a significant competitor with conventional aeration for removal of BOD_5 from wastewater. The process has been studied since 1970 at the EPA-DC Pilot Plant[1,2] in Washington, D.C.; the study has revealed several advantages over conventional aeration.

The high oxygen transfer rates with pure O_2 produce high dissolved oxygen (D.O.) concentrations and permit the use of high mixed liquor concentrations and thus small reactors. The high D.O. in the reactor minimizes periods of low D.O., such as occur in clarification, and increases O_2 transfer into the center of the sludge mass. The process exhibits apparently higher metabolic rates and good resistance to shock organic loadings. The high oxygen transfer rates provide process flexibility for minimizing sludge production through easily increased endogenous respiration in the reactor.

In evaluating oxygen applications, the process stability and reduced reactor size must be weighed against the cost of the oxygen and the mechanical systems employed in its utilization. In addition, the increased mixed liquor concentrations possible in the oxygen process increases the mass loading on the clarifier, which increases clarifier size. Finally, sludge reduction through increased endogenous respiration requires a stoichiometric amount of O_2 for each unit amount of COD destroyed. The final design of the oxygen process and its solids-handling system requires the consideration and balancing of these factors with the ultimate cost benefit to be fully determined in the market place over the next few years.

With the current usage of the O_2-activated sludge process, consideration of its compatibility with other wastewater treatment processes and development of techniques to reduce mass loading on the oxygen clarifier are needed. In previous work, alum addition[1] to remove phosphorus (Equation 1) was applied to the O_2 process on a wastewater of moderate alkalinity (130 mg/l as $CaCO_3$). With the recirculation of O_2 within each reactor stage, the CO_2, increasing in recirculated process gas, normally suppressed the Washington, D.C. effluent pH to a range of 6.4 to 6.6 without alum addition. In the study with alum addition, the Al/P weight ratio was incrementally increased from 1.1:1 to 1.85:1 during a period of approximately one month. At an Al/P weight ratio of 1.85:1, the acid produced (Equation 2) by the hydrolysis of excess Al^{+++} further reduced the O_2 process wastewater pH from its normal 6.4 to 6.6 range to less than 6.0.

$$Al^{+++} + PO_4^{=} \rightarrow AlPO_4 \qquad (1)$$

$$Al^{+++} + 3HOH \rightarrow Al(OH)_3 + 3H^{+} \qquad (2)$$

At the low pH, the process immediately removed more than 90% of the P but within three days exhibited a dispersion of the biological and chemical solids into the final effluent. At a 1.4:1 Al/P ratio, the process wastewater pH and alkalinity decreased only slightly and the bio-mass dispersion did not occur but the alum addition removed only 80% of the P. During the alum addition, the chemical precipitates increased the amount of solids in the reactor and the solids loading to the final clarifier.

Therefore, two studies on the activated sludge process were performed at the EPA-DC Pilot Plant: one, to further evaluate alum addition for phosphorus removal using lime for pH control; the other, to evaluate a step-feed configuration without mineral addition to reduce the solids loading to the final clarifier.

SECTION 2

CONCLUSIONS

ALUM ADDITION STUDIES

In earlier work[1] with alum addition in the oxygen-activated sludge process on D.C. wastewater, increasing the Al/P dosage weight ratio to 1.85:1 depressed the process pH from approximately 6.4 to below pH 6. Within three days, the process exhibited a dispersion of both chemical and biological solids into the process effluent. In the current study on alum addition for phosphorus removal, lime slurry added to the influent wastewater maintained the effluent pH above 6.4 and prevented sudden dispersion of the biological and chemical solids in the clarifier.

The alum addition in the oxygen-activated sludge process, evaluated at four average levels of Al/P dosage weight ratios (1.1:1, 1.45:1, 1.8:1, and 2.66:1), produced a maximum phosphorus removal of 86% at the 1.81 Al/P weight ratio.

At the 1.8:1 Al/P weight ratio, the process exhibited maximum removals of BOD_5 (92%) and suspended solids (84%), with an average BOD_5 residual of 7.4 mg/l and a suspended solids residual of 17 mg/l.

At an average Al/P weight ratio of 2.66, the process exhibited a gradual increase of nonbiological solids in the process effluent. The excessive amounts of $Al(OH)_3$ accumulated during 14 days of operation gradually increased clarifier instability and forced discontinuance of the alum feed.

The average lime dose required to maintain the process pH of 6.4 was 15 and 37 mg/l at respective Al/P weight ratios of 1.8 and 2.66:1. Based upon a 1:1 molar Al/P requirement for precipitation of the phosphorus, these lime dosages corresponded approximately stoichiometrically to the milli-equivalents of acid produced by the hydrolysis of excess Al^{+++} ions to $Al(OH)_3$.

Lime dosages above the stoichiometric requirements for hydrolysis of excess Al^{+++} ions were also required to neutralize the HNO_3 produced when the process was partially nitrifying.

Solids production of O_2-activated sludge with alum addition increased over that for operation of the biological process without mineral addition. During operation with Al/P weight ratios ranging from 1.1:1 to 2.66:1 and for an overall Al/P weight ratio of 1.53:1, the solids production averaged approximately 1.34 gm of solids per gm of applied BOD_5, of which 0.99 gm of solids per gm of applied BOD_5 was in the wasted sludge.

STEP-FEED STUDIES

The O_2-activated sludge process operated in a step-feed configuration, as when operated in the conventional "plug" flow configuration, removed essentially all soluble substrate, with the soluble effluent BOD_5 averaging less than 3 mg/l.

The step-feed configuration exhibited a MLSS profile that decreased from nearly 10,000 mg/l in the first stage to about 4,000 mg/l in the fourth stage and averaged 6,500 mg/l. The 4,000 mg/l MLSS in the fourth stage produced a desirable and modest solids loading [clarifier flux of about 115 $kg/d/m^2$ (23 $lb/d/ft^2$)]. Thus, the step-feed configuration permitted a high average MLSS without a high flux loading to the clarifier.

The step-feed configuration for the O_2 process, however, achieved only a 50% utilization of the O_2 gas feed compared to the typical 90% utilization for the "plug" flow configuration. If further work confirms the 50% O_2 utilization efficiency, the step-feed configuration will not be an economical alternative in the O_2-activated sludge process as practiced at the EPA-DC Pilot Plant.

The solids production in the step-feed configuration at an SRT of approximately 11 days was 0.5 gm of solids produced per gm of applied BOD_5, with approximately half of the solids production leaving the process in the secondary effluent.

The O_2-activated sludge process in the step-feed configuration produced approximately 70% nitrification of the TKN at an SRT of 11 days and removed approximately 40% of the total nitrogen.

The settling velocities of oxygen-activated sludge mixed liquor in the step-feed configuration were good. At a MLSS of approximately 4,000 mg/l, the solids exhibited initial settling velocities of 5.2 m/hr (17 ft/hr) which was typical of summer time settling of O_2-activated sludge solids.

SECTION 3

RECOMMENDATIONS

ALUM ADDITION STUDIES

In the study, the oxygen-activated sludge system functioned satisfactorily at an average alum dosage (Period 3) which corresponded to an Al/P weight ratio of 1.8. Increasing the average alum dosage to correspond to an Al/P weight ratio of 2.66 (Period 4), even with pH control, produced a gradual process failure. In addition, without continuous phosphorus analyses on the primary wastewater, the control of the daily and instantaneous Al/P ratio was not very good. Thus, the process behavior and the lower limit of the effluent residual P concentration needs further study in a system with effective instantaneous Al/P dosage control at Al/P weight ratios between 1.8 and 2.66.

STEP-FEED STUDIES

While the step-feed configuration on the oxygen-activated sludge process reduced the mass loading to the final clarifier and also achieved efficient BOD_5 removal, the observed poor oxygen utilization efficiency would prevent in the step-feed configuration practical applications of the oxygen contacting system employed in the EPA-DC Pilot Plant. Confirmation of the observed oxygen utilization efficiency is needed. Work on alternate oxygen contacting approaches should also be performed to determine if practical (reasonable oxygen utilization) operations can be achieved for an oxygen step-feed activated sludge configuration.

SECTION 4

PILOT SYSTEM

In the EPA-DC Pilot Plant, the oxygen-activated sludge equipment (Figure 1) consisted of a four-stage reactor of 30.5 m^3 (8,080 gallon) liquid volume, and two center-feed gravity settlers with 7.25 m^2 (78 ft^2) of clarification area in each settler and water sidewall depth of 3.4 m (11.1 ft.). The gas-tight reactor included submerged hydraulic entrances and exits with water seals where the mixing equipment enters the reactor.

The reactor was divided into four mixing stages. Oxygen was introduced into the first stage; its flow controlled by a pressure regulator to maintain a pre-selected reactor gas pressure, usually between 2.54 cm (1 inch) and 9.16 cm (4 inches) of water. The oxygen flowed from the first through the fourth stage and for normal "plug" flow operation was co-current to the mixed liquor flow. Compressors on each stage recirculated the overhead gas through a rotating diffusion-impeller to provide mixing of the bio-mass and to disperse the recirculating gas. Variations in the compressor recirculation rate, selected manually by the operator, were used to control the dissolved oxygen level for plug flow between 4 and 8 mg/l.

In the center-feed settlers, two sludge withdrawal mechanisms were employed: one settler mechanism employed a hydraulic syphon; the other, a conventional plow to force the sludge into a central sludge well. Sludge recirculation was achieved by variable-speed Moyno sludge pumps.

In the study of mineral addition, the reactor was operated with various diurnal flow patterns in a "plug" flow configuration with District of Columbia primary effluent as the process feed. Lime slurry was added to the wastewater at the reactor influent and alum was added at the reactor discharge. The lime slurry dosage was controlled in a flow-proportioned (feedforward), pH error (feedback) analog control loop by a submerged pH probe located in the first reactor stage. The pH set point was manually altered by the operator to maintain the final process effluent pH in the range of 6.3 to 6.8. The manually-selected alum dosage was proportioned to flow by using a pneumatically controlled metering pump.

In the step-feed study, the District of Columbia primary effluent was divided by a splitter box into three separate equal streams and pumped at a steady flow into the last three stages of the reactor. Alum was not added to the process. In the step-feed study, the O_2 reactor employed the normal contacting procedures and gas flow configuration.

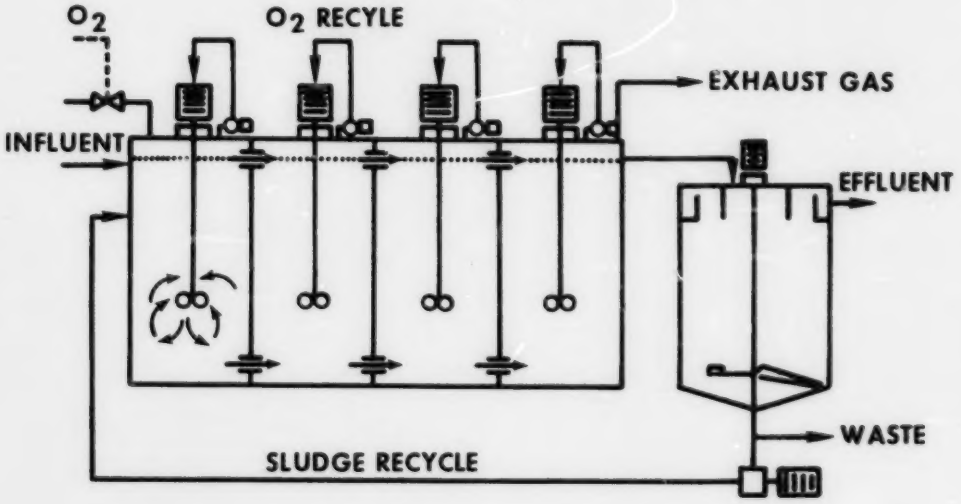

Figure 1. Oxygen aeration system.

SECTION 5

ANALYTICAL PROCEDURES

In the evaluation of the process performance, BOD samples were always manually composited proportional to flow over a 24-hour period. All other appropriate samples were composited for 24-hour periods on Tuesday through Thursday and for 48-hour periods on Friday through Monday. All samples were stored at 3°C to minimize biological activity. All samples except for BOD and suspended solids were also acidified with 1 ml of H_2SO_4 per 600 ml of sample.

The 5-day biological oxygen demand (BOD_5) of the composite samples was determined by means of the probe method[3]; the ammonia[3] and nitrate-nitrite[4], by use of a Technicon Automatic Analyzer. The total organic carbon (TOC)[5] was measured on a Beckman Carbonaceous Analyzer. The total phosphorus[6] was determined by means of the persulfate method. All other analyses employed Standard Methods[7]. Soluble phosphorus and soluble BOD were filtered through a standard-glass suspended-solids filter before analyses.

Batch settling tests on the process mixed liquor were periodically conducted in a stirred 15.3 cm (6-inch) diameter by 3.3 m (10 feet) long "plexiglas" settling column. The slope of the interface height versus time provided the initial settling velocity of the mixed-liquor suspended-solids concentration at the existing wastewater temperature.

Dissolved oxygen uptake rates on samples of the mixed liquor from various reactor stages were conducted as appropriate. In the test, the mixed liquor sample, usually with 4 to 8 mg/l of D.O., was placed in a standard BOD bottle; and the dissolved oxygen concentration was continuously measured with a D.O. meter as a function of time. The oxygen uptake rate was then calculated as the slope of the D.O. versus time plotted for the mixed liquor solids concentration in the sample.

SECTION 6

ALUM ADDITION STUDIES

The operation of the process during alum addition studies was divided into five operating periods (Table 1) and a two-week period in February (period 4a and 4b) for correcting an accumulation of excess solids in the clarifier. The combination of reactor contact time and average MLVSS provided relatively constant F/M (0.18 to 0.24 gm of BOD_5/gm of MLVSS/day) and SRT (4.7 to 6.0 days) operation during the five operating periods. The diurnal flows (Table 2) were usually varied for an approximate 1.5:1 peak to average flow ratio, although in November the variation was 2:1 and in December 1.2:1. During the study, the influent pH averaged 7; the effluent pH was maintained at or above pH 6.4 with the addition of lime slurry.

During the first four periods, the average alum dose was increased from a 1.1 to a 2.66 Al/P weight ratio. During the last period (March 1-20), the Al/P weight ratio was averaged at 1.78. Surprisingly, the lime dosage (Table 1) decreased with increasing alum dosages in the first four periods. Actually, in the first period (November) with little excess Al^{+++} ions, HNO_3 production by nitrification within the O_2 process produced part of the lime demand. In December, a combination of partial nitrification, an elevated effluent pH of 6.7 with corresponding CO_2 neutralization (the normal operating pH is approximately 6.4 for O_2-activated sludge in Washington, D.C.), and the hydrolysis of the excess Al^{+++} ions (Equation 2) all contributed to the 58 mg/l CaO dosage. In January, the elevated pH of 6.6 and the hydrolysis of the excess Al^{+++} ions determined the lime requirement.

In the last two periods (February 1-14 and March 1-20) with the effluent pH at 6.4 and without nitrification, the lime dosages (15 mg/l of CaO at a 1.78 Al/P ratio and 37 mg/l at a 2.66 Al/P ratio) corresponded almost stoichiometrically to the amount of acid produced by the hydrolysis of the excess Al^{+++} ions (Equation 2). Clearly, only modest lime doses were required to prevent pH depression caused by the addition of excess mineral salts for efficient phosphorus removal in the O_2 process. It should be emphasized, however, that the combination of partial nitrification and elevated effluent pH (above that normally produced without mineral addition by CO_2 adsorption in the process wastewater) significantly increased the lime dosage.

During the entire study, the sludge production (Table 2) averaged 1.34 gm of solids/gm of BOD_5 applied. The average operating conditions corresponding to the sludge production was an influent BOD_5 of 101 mg/l, an Al/P of 1.53, and an alum dose of 115 mg/l. In January, the decreased concentration of sludge at the bottom of the clarifiers and the increased capture of solids produced an

TABLE 1. REACTOR OPERATING CONDITIONS FOR O_2-ACTIVATED SLUDGE WITH ALUM

Period	1	2	3	4	4a	4b	5
Date	Nov '72	Dec '72	Jan '73	Feb 1-14	Feb 15-22[c]	Feb 23-28[d]	Mar 1-20
Reactor Detention hrs	2.6	2.5	2.76	2.95	3.43	3.0	3.0
F/M gm BOD_5 (gm MLVSS) (day)	0.21	0.22	0.20	0.18	0.16	0.28	0.24
SRT days	5.8	5.5	6.0	5.4	3.5	4.5	4.7
MLSS							
mg/l	6915	6840	6760	7060	6950	5380	5375
% Vol.	65	61.3	61	58.5	62.5	66	65.6
CaO Dose							
mg/l	50.7	58.0	38.7	37.4	20	15	15.1
pH							
In	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Out	6.4	6.7	6.6	6.4	6.7	6.5	6.4
Alkalinity as $CaCO_3$, mg/l							
In	127	116	130	114	121	130	129
Out	99	134	136	101	152	126	116
Alum Dose[a], mg/l	84	105	142	184	---	105	136
Al/P Weight Ratio[b]	1.1	1.45	1.82	2.66	---	1.1	1.78
$(NO_3 + NO_2) - N$, mg/l in Eff.	7.28	3.53	0.46	0.25	0.14	---	0.15

[a] Alum as $Al_2(SO_4)_3 \cdot 14H_2O$ average daily dosage 115 mg/l.

[b] Average daily Al/P for November-March 1.53.

[c] Alum addition discontinued; heavy wasting applied to remove accumulated chemical solids.

[d] Alum addition resumed at a 1.1 Al/P weight ratio; clarifier bed level reestablished at usual 5-6 ft. depth.

TABLE 2. CLARIFIER OPERATION AND SLUDGE PRODUCTION OF O_2 ACTIVATED SLUDGE WITH ALUM ADDITION

Period	Date	Average Clarifier Overflow (m/d)	Peak to Average Flow	SVI (ml/g)	Recycle Rate (%)	Underflow Solids (%)		Solids Production (gm solids/gm BOD_5 applied)	
						Plow	Tow-Bro	Produced[a]	Wasted[b]
1	Nov. 1972	19.2	2	44	43	2.39	2.19	1.24	.93
2	Dec. 1972	19.9	1.2	41	47	2.15	2.14	1.33	1.05
3	Jan. 1973	18.3	1.45	47	52	2.04	2.04	0.91	0.73
4	Feb. 1-14	17.1	1.6	48	52	2.0	2.04	1.68[c]	1.34
4a	Feb. 15-22	14.7	1.0	58	47	2.43	2.34	2.83[c]	1.88
4b	Feb. 23-28	16.7	1.6	56	46	1.57	1.76	1.30[c]	.88
5	Mar. 1-20	16.8	1.55	58	50	1.63	1.83	1.34	.82

[a] The average sludge production for the study was 1.34 gm/gm of applied BOD_5. The average operating characteristics corresponding to the sludge production were an applied BOD_5 of 101 mg/l, an Al/P of 1.53, and an alum dose of 115 mg/l.

[b] The average sludge wasted for the study was 0.99 gm/gm of applied BOD_5 under conditions as in note 1.

[c] The average sludge production for Feb. 1-28 was 1.92 gm/gm applied BOD_5.

increasing inventory of solids in the clarifiers. Although increased wasting rates were employed in early February, the high alum dosage for February 1-14 further increased the total solids inventory and the height of the sludge blanket in the clarifiers. Increasing amounts of solids, chiefly chemical solids, appeared in the clarifiers' overflow. To eliminate the increased solids inventory and the excessive carryover of solids in the effluent, the alum addition was discontinued for eight days in February (15-22) and heavy wasting was applied to the process. Thus, while solids production during the first two periods (November and December) and last period (March 1-20) represented production at approximate equilibrium conditions, the sludge production in January was lower and in February was higher than expected production at equilibrium conditions.

The BOD, COD, SS, and P removals (Table 3) generally increased with Al/P dosage ratios until the 2.66 Al/P ratio was applied. The best removals occurred at the 1.8 Al/P ratio. As indicated earlier, at the 2.66 Al/P ratio the process exhibited a gradually increasing carry-over of chiefly chemical solids. The accumulated solids from January and the high Al/P dosage caused increased sludge blanket depth within the clarifier and contributed to the deterioration in effluent quality. The average pH was maintained at 6.4 and the increased solids carry-over did not result from low pH. The solids in the process did not disperse suddenly; but even with an increased wasting of sludge, the continued addition of a large excess alum caused further deterioration. The alum feed was discontinued on February 15 and high wasting rates were applied to the process to eliminate the excess sludge. After eight days of operation, the sludge blanket level was restored to the normal operating level and alum dosing was resumed, but at a 1.1 Al/P ratio. During the heavy wasting, heavy solids carry-over occurred in the clarifier. Although the BOD removal declined only moderately (from about 90% to 81%), COD, SS, and phosphorus removals declined markedly. Thus, many of the materials in the effluent were biologically difficult to degrade or were chemical solids.

With the resumption of alum addition, the process exhibited satisfactory BOD removals of about 85%, but high solids, COD, and P continued to appear in the effluent for the remainder of the study. Clearly, the last period (March 1-20) of the study did not represent typical product quality for mineral addition in the O_2 process.

The process influent and effluent exhibited a wide daily variation in phosphorus content during the operation from November through January. Since the alum dosage was proportioned to flow, the daily variation in phosphorus content, with some drift in the alum metering pump, produced the range of Al/P shown in Figure 2. This figure clearly revealed not only the decrease in P with increasing Al/P dosage ratio, but also a wide variation in daily P removal. With the combined sewers in the District of Columbia causing the wide daily variation in influent P, we decided that improved Al/P dosage control would be useful. During the study, fully automatic control, however, was not employed because it required the development of a continuous analyzer for influent P.

TABLE 3. EFFLUENT QUALITY OF O_2 ACTIVATED SLUDGE WITH ALUM ADDITION[a]

		BOD(mg/l)			COD(mg/l)			SS(mg/l)			P(mg/l)			N(mg/l)		
Period	Al/P	In	Out	% Rem.	In	Out	% Rem.	In	Out	% Rem.	In	Out	% Rem.	In	Out	% Rem.
1	1.1	104	19.1	82	238	48	80	112	33	70	6.98	1.84	74	23.8	12.7	48
2	1.45	100	9.5	90	241	49	80	116	30	74	6.75	1.72	75	26.9	13.3	36
3	1.82	97	7.4	92	246	39	84	110	17	84	7.24	1.05	86	25.9	18.8	28
4	2.66	91	10.2	89	220	45	80	104	31	70	6.45	1.32	79	23.2	18.0	22
4a	----	100	19.3	81	247	103	58	110	96	13	7.22	4.64	36	22.8	20.9	8
4b	1.1	91	12.7	86	249	82	63	104	49	53	8.55	4.05	53	23.5	19.5	17
5	1.78	108	16	85	246	76	69	117	56	52	7.12	3.26	54	25.0	19.6	22

[a]Percentage removals based upon primary effluent.

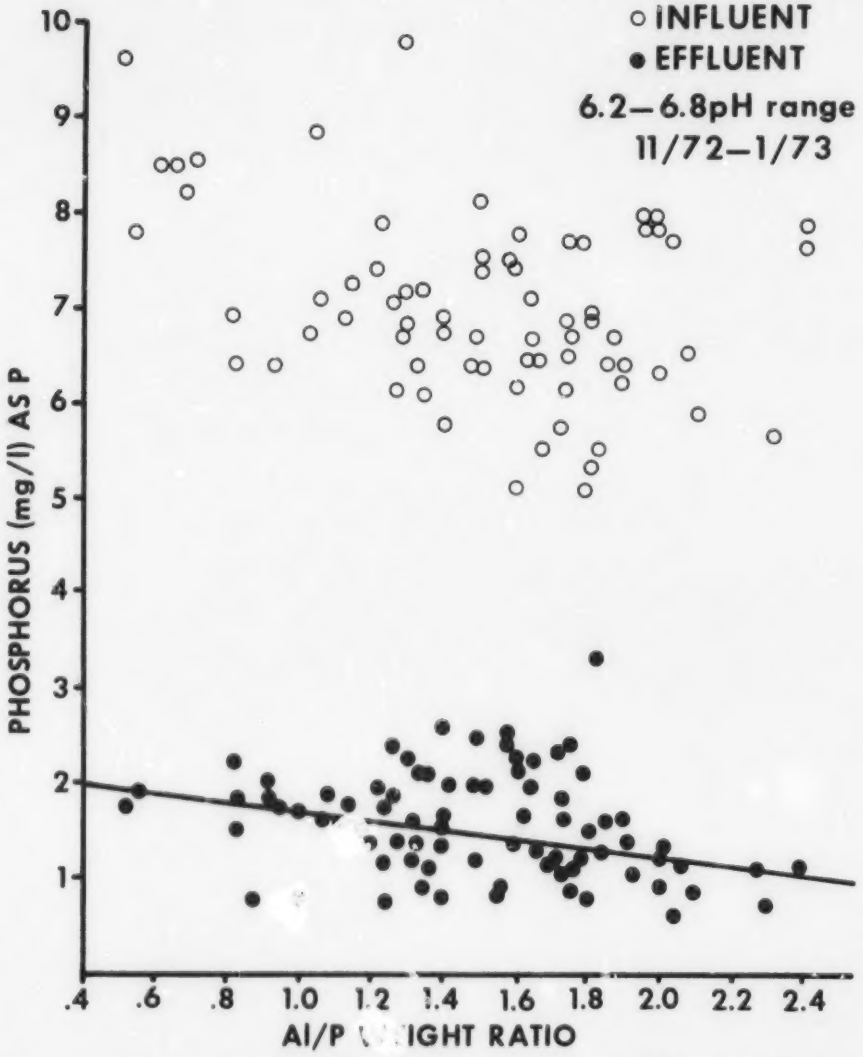

Figure 2. Phosphorus removal by alum addition in O_2 activated sludge.

When alum addition to the O_2 process improved the solids capture in the clarifier, it also may have moderately improved the initial settling velocities for any given MLSS and wastewater temperature. The initial settling velocities (Table 4) of the MLSS fall within the range of previously observed settling velocities[2] (Figure 3) for oxygen-activated sludge without alum addition. However, in earlier work[2] at the EPA-DC Pilot Plant, the initial settling velocities of the MLSS without alum addition during similar seasons (November-February) tended to fall within the lower portions of the observed range. In the current study, the initial settling velocities of the MLSS with alum addition clustered in the upper portion of the observed range. Unfortunately, without a control (parallel O_2 process without alum addition) for direct comparison, it was not possible to determine whether the apparent (compared to earlier observations) improvement was related to alum addition, and whether this improvement in initial settling velocities was great enough to compensate for the increased clarifier mass-loading caused by the precipitated chemical solids. In contrast to the apparent increase in the settling velocities of the MLSS, the underflow solids concentration in the clarifiers decreased with increasing alum dosage (Table 2). (The thickening characteristics in the last half of February and March should not be considered representative because of the heavy wasting in mid-February).

Finally, filtration of the alum-O_2 process effluent through dual and multi-media filters was performed as an additional compatibility study. The filtration study, unfortunately, was conducted during the operation with the highest Al/P dosage range (2.66:1) and did not correspond to the period of best alum addition-O_2 operation. Thus, the solids concentration entering the filter were higher than those during the most efficient process operation. Two filter media were employed (Table 5), a dual media and a multi-media. In the multi-media, two different coals, one of specific gravity 1.4 and the other of specific gravity 1.6, were used to produce a four media bed. Laboratory Millipore filtration (0.45μ) of the effluents was performed for comparison with the in-depth pilot filtration. In the brief tests, the filters were backwashed after a headloss of 3.18 meters (125 inches) of water occurred across the filter. The filter cycles averaged approximately 10 hours with a backwash requirement of 15% of the product volume. The solids loading per filter cycle (in kg of solids per square meter of filtration area) ranged from 18.8 to 28.2 (.38 to .58 lb of solids/ft^2) and were similar to typical loadings for filtration of other mineralized activated-sludge effluents in the pilot plant[9, 10].

The filter study revealed filtration performance (Table 6) on mineralized O_2 process effluent similar to performances observed in earlier EPA-DC pilot studies[10] of mineralized step-aeration activated-sludge effluent. Although the media specifications in the two studies were different, the solids removals of 60 to 75% in the current study compared well with the 62 to 78% removals of the earlier work[10] on the alum-air activated sludge effluent. With higher Al/P ratios and a lower effluent pH, the phosphorus residuals in the current study were lower than the average residuals reported in the earlier work[10] but were similar to those residuals observed in that earlier work when the effluent pH of the air system was in the 6.4 to 6.5 pH range.

TABLE 4. SETTLING RATES FOR O_2 ACTIVATED SLUDGE WITH ALUM ADDITION

DATE	TEMP (^{o}C)	SVI (ml/gm)	MLSS (mg/l)	ISV (m/hr)
11/1/72	20.0	46	5800	2.9
12/15/72	16.7	41	6540	3.1
12/22/72	15.0	--	8010	4.1
12/27/72	16.0	37	6650	2.7
1/10/73	16.7	42	7480	2.4
1/12/73	17.2	51	7340	3.1
1/29/73	15.0	51	5820	2.6
2/1/73	15.7	48	6870	2.2
2/27/73	14.5	51	5540	2.4
3/7/73	15.5	71	5740	2.3
3/14/73	16.0	54	4860	3.0

TABLE 5. FILTRATION SYSTEM ON ALUM-O_2 SECONDARY EFFLUENT

Media Specifications

Dual-media	Depth (m)	Size (mm)	Specific Gr.
Coal	0.61	1.24-1.44	1.5
Sand	0.305	0.6-0.7	2.6
Multi-media			
Coal I	0.406	1.5-1.6	1.4
Coal II	0.203	1.0-1.1	1.6
Sand	0.229	0.4-0.5	2.6
Ilmenite	0.076	0.2-0.35	4.65

Operating Conditions

Diurnal flow cycle, peak to average	1.6:1
Average flow (m/min)	0.196
Average cycle time (hours)	10
Head loss at backwash (m)	3.18
Backwash requirement (% of product)	15
Backwash rate (m/min)	0.81
Surface wash rate (m/min)	0.12
Filter solids loading $kg/m^2/cycle$	18.8-28.2

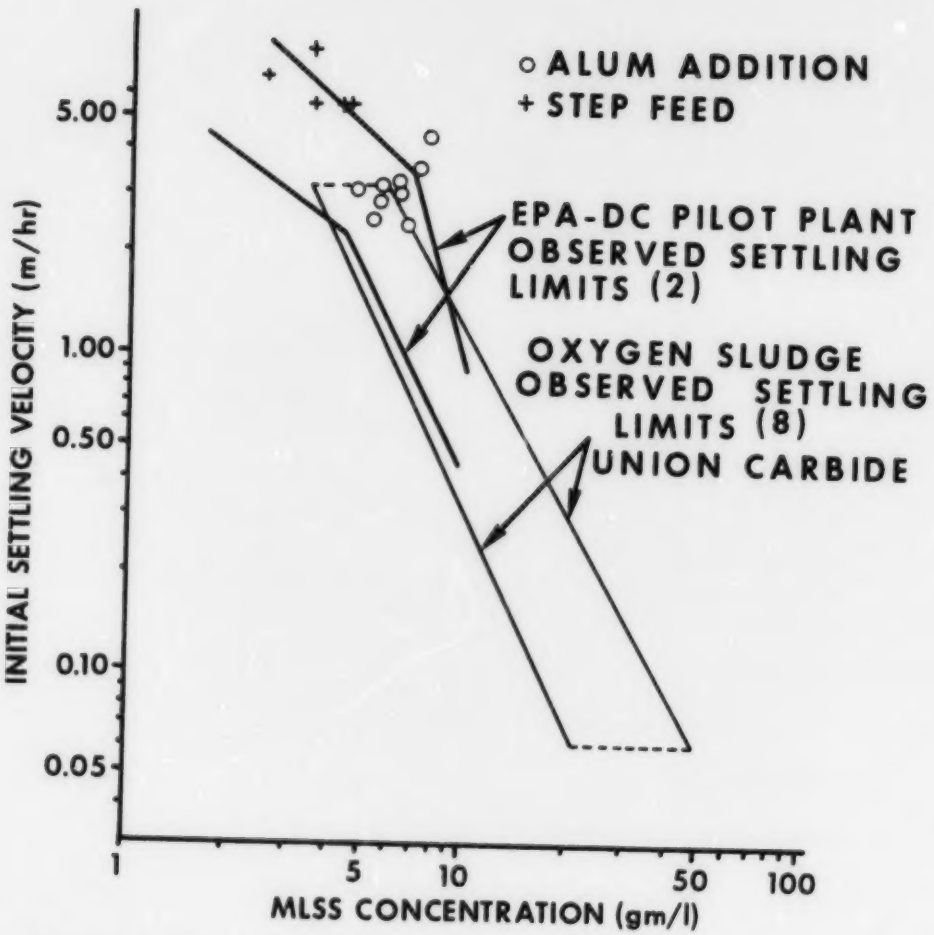

Figure 3. Initial settling velocities of oxygen MLSS as a function of concentration.

TABLE 6. FILTER PERFORMANCE ON ALUM-O_2 SECONDARY EFFLUENT

Pilot Filters

Date	Sample	SS	BOD	COD	P	Al/P Ratio
2/6/74	Inf. (mg/l)	25	7.3	36	0.805	3.95
	Dual Eff. (mg/l)	6	4.7	29	0.365	
	% Removal	72	35	19	55	
	Multi Eff. (mg/l)	6	3.3	19	0.346	
	% Removal	72	55	47	57	
2/7/74	Inf. (mg/l)	27	7.0	35	0.926	4.13
	Dual Eff. (mg/l)	11	4.5	25	0.405	
	% Removal	60	36	29	56	
	Multi Eff. (mg/l)	--	3.3	19	0.150	
	% Removal	--	53	46	83	
2/14/74	Inf. (mg/l)	32	12.0	54	2.06	1.99
	Dual Eff. (mg/l)	12	6.9	32	0.531	
	% Removal	62	43	41	74	
	Multi Eff. (mg/l)	9	4.8	32	0.346	
	% Removal	72	60	41	83	

Millipore Filtration

	2/6/74	2/7/74	2/14/74
Eff. P	0.652	0.74	1.72
% Removal	19	20	17

With the small data base of the current study, a meaningful comparison between media types cannot be made. However, comparison between the pilot in-depth filtration and the laboratory Millipore filtration is appropriate. Filtration through the in-depth dual and multi-media filters removed more than 50% of the residual P. Filtration through the 0.45μ laboratory Millipore filters removed only approximately 20% of the residual P. These results confirmed similar observations during extensive filtration studies[9] on the effluent from the three-stage activated sludge pilot system in the EPA-DC Pilot Plant. The in-depth filtration improved the removal of phosphorus, either because of increased precipitation and flocculation on the filter bed or because of adsorption of the P on the Al $(OH)_3$ and other materials in the filter bed.

SECTION 7

STEP-FEED STUDIES

In the step-feed study, the operation of the O_2-activated sludge process with an equal split of the feed into the last three reactor stages was initiated (Table 7) in late June at a steady flow with a reactor detention time of about 1.85 hours and with a steady clarifier overflow rate of approximately 27.5 m/d (675 gpd/ft^2). Mineral addition was not employed. Data acquisition was initiated on July 20, 1973. The process was first operated at an F/M of about 0.23 gm BOD_5/gm MLVSS/day and at an SRT of 11 days. Later the F/M was increased to 0.32 gm BOD_5/gm MLVSS/day.

The important advantage of the step-feed configuration was the MLSS profile (Table 7) through the reactor stages. The MLSS decreased from nearly 10,000 mg/l in the first stage to about 4,000 mg/l in the last stage and averaged around 6,500 mg/l. Thus, the step-feed configuration produced a desirable and modest solids loading (clarifier flux) of about 115 kg/d/m^2 (23 lb/day/ft^2) and a high average MLSS without a high flux loading to the clarifier.

At the operating SRT of 11 days, the process exhibited a low sludge production of about 0.5 gm of solids/gm BOD_5 applied, with about half of the solids production in the waste sludge stream and the rest in the secondary effluent. The MLSS entering the clarifier exhibited typically excellent settling velocities for summer operation (Figure 4). The initial settling velocities in the 15.25 cm diameter by 2.44 m high column ranged from 5.3 to 8.3 m/hr (17.4 to 27.2 ft/hr) (Table 8) and, as typical of warm-water settling rates, clustered in the upper portion of the earlier observed[2] settling velocities (Figure 3).

The effluent quality from the step-feed operation was excellent (Table 9). With nitrification in the process, an allyl-thiourea inhibited BOD_5 (0.5 mg/l of allyl-thiourea) and an uninhibited filtered BOD_5 were obtained on the final effluent. As in conventional plug-flow O_2-activated sludge[1], the process operated in the step-feed configuration reduced the soluble BOD_5 to less than 3 mg/l and the total residual BOD_5 (inhibited) to less than 10 mg/l. The step-feed process also efficiently removed COD (78 to 85%) and suspended solids (70 to 87%). Without alum addition, the process removed from 17 to 42% of the total P. At the high SRT, the system partially nitrified, converting about 70% of the TKN to nitrate, and provided a total nitrogen removal of about 40%. The nitrification and CO_2 reduced the effluent pH to 6.3. As expected, the nitrification also reduced the effluent alkalinity.

The step-feed configuration, because of treatment efficiency and clarifier loading characteristics, is especially well suited to the oxygen-activated sludge process. However, the key to its application is the efficiency of

TABLE 7. STEP-FEED, O_2-ACTIVATED SLUDGE OPERATING CONDITIONS

REACTOR

Period 1973	Detention Time (hr.)	F/M gm BOD_5 / (gm MLVSS)(day)	SRT (days)	Average MLSS (mg/l)	Average MLSS (% Vol.)	MLSS (mg/l) Stage 1	Stage 2	Stage 3	Stage 4
July 20-31	1.81	0.26	10.7	6500	73	9800	6720	5180	4310
Aug. 1-31	1.84	0.23	11.5	6730	74	10,700	7060	5020	4150
Sept. 18-26	1.88	0.32	----	5830	74	8970	6040	4570	3760

CLARIFIER AND SLUDGE PRODUCTION

Period 1973	Flow Rate (m^3/d)	Clarifier Overflow (m/d)	Clarifier Flux ($kg/d/m^2$)	SVI (ml/g)	Underflow Solids (%) Flow	Underflow Solids (%) Tow Bro	Recycle Rate (%)	gm solids/gm BOD_5 applied: Produced	gm solids/gm BOD_5 applied: Wasted
July 20-31	405	28.0	120	50	2.06	1.70	53	0.49	0.19
Aug. 1-31	399	27.5	115	37	2.15	1.84	51	0.50	0.24
Sept. 18-26	390	27.0	102	49	2.16	1.78	42	----	----

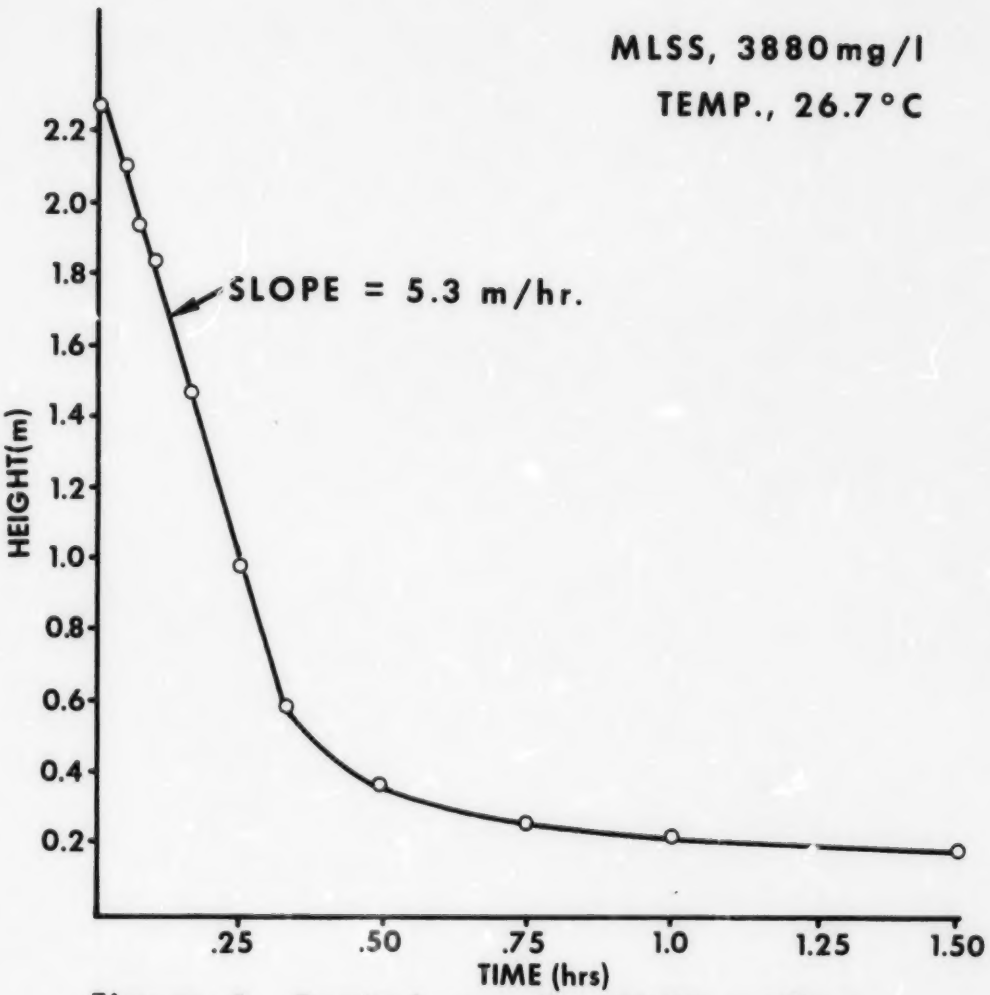

Figure 4. Typical step-O_2 MLSS settling.

TABLE 8. INITIAL SETTLING VELOCITIES[a] OF STEP-FEED, O_2-ACTIVATED SLUDGE

SVI (ml/g)	TEMP (^{o}C)	MLSS (mg/l)	ISV (m/hr)
70	24.5	2620	6.9
53	25.0	4360	5.5
60	24.7	3860	8.3
39	26.7	3880	5.3
34	26.2	4510	5.5

[a] Dynamic settling in 15.25 cm dia. by 2.44 m long settling column mixed at 10 rph.

TABLE 9. STEP-FEED, O_2-ACTIVATED SLUDGE EFFLUENT QUALITY[a]

CARBON AND SOLIDS

Period 1973	BOD_5 In (mg/l)	BOD_5 Out[b] (mg/l)	BOD_5 Rem. (%)	Filt. BOD_5 Eff. (mg/l)	COD In (mg/l)	COD Out (mg/l)	COD Rem. (%)	SS In (mg/l)	SS Out (mg/l)	SS Rem. (%)
July 20-31	----	---	--	---	208	46	78	95	28	70
Aug. 1-31	88.5	9.7	89	2.8	208	43	79	100	23	77
Sept. 18-26	111	8.3	93	2.4	248	38	85	120	15	87

PHOSPHORUS AND NITROGEN

Period 1973	pH In	pH Out	Alkalinity In (mg/l)	Alkalinity Out (mg/l)	Total P In (mg/l)	Total P Out (mg/l)	TKN In (mg/l)	TKN Out (mg/l)	$(NO_3 + NO_2)$-N In (mg/l)	$(NO_3 + NO_2)$-N Out (mg/l)	Total N Removal (%)
July 20-31	6.9	6.3	126	74	5.78	4.77	20.2	6.2	0.09	5.8	41
Aug. 1-31	6.9	6.3	129	80	5.51	4.40	20.6	6.4	0.05	5.4	43
Sept. 18-26	7.0	6.3	154	94	7.45	4.27	24.5	7.1	0.05	6.7	44

[a] All % removals based on primary effluent.

[b] Inhibited BOD_5 (0.5 mg/l allyl thiourea inhibitor)

utilization of the O_2 gas feed to the process. Prior to the step-feed study, the equipment was completely renovated and the O_2 recirculation compressors were replaced.

During the summer operation with the new and renovated equipment, the system exhibited unknown oxygen losses. Finally in September, all leaks were eliminated and brief oxygen balances were performed on the process. Two approaches to the oxygen balances were employed. One approach was employed to compare the measured O_2 in the inlet gas flow with the O_2 in the outlet gas flow and in the effluent stream (D.O.). The second approach was employed to compare measured inlet O_2 with the oxygen used as measured by dissolved oxygen uptake rates (Figures 5 and 6) in each of the process stages. Both approaches to the oxygen balance (Table 10) revealed about a 50% utilization of the inlet O_2. Further work is needed to confirm these O_2 balances and in particular to assess the increase in mechanical energy input needed to decrease the percent oxygen in the exhaust gas. However, if confirmed, oxygen usage of about 50% will eliminate the step configuration as a practical alternative to the O_2 process as practiced at the EPA-DC Pilot Plant.

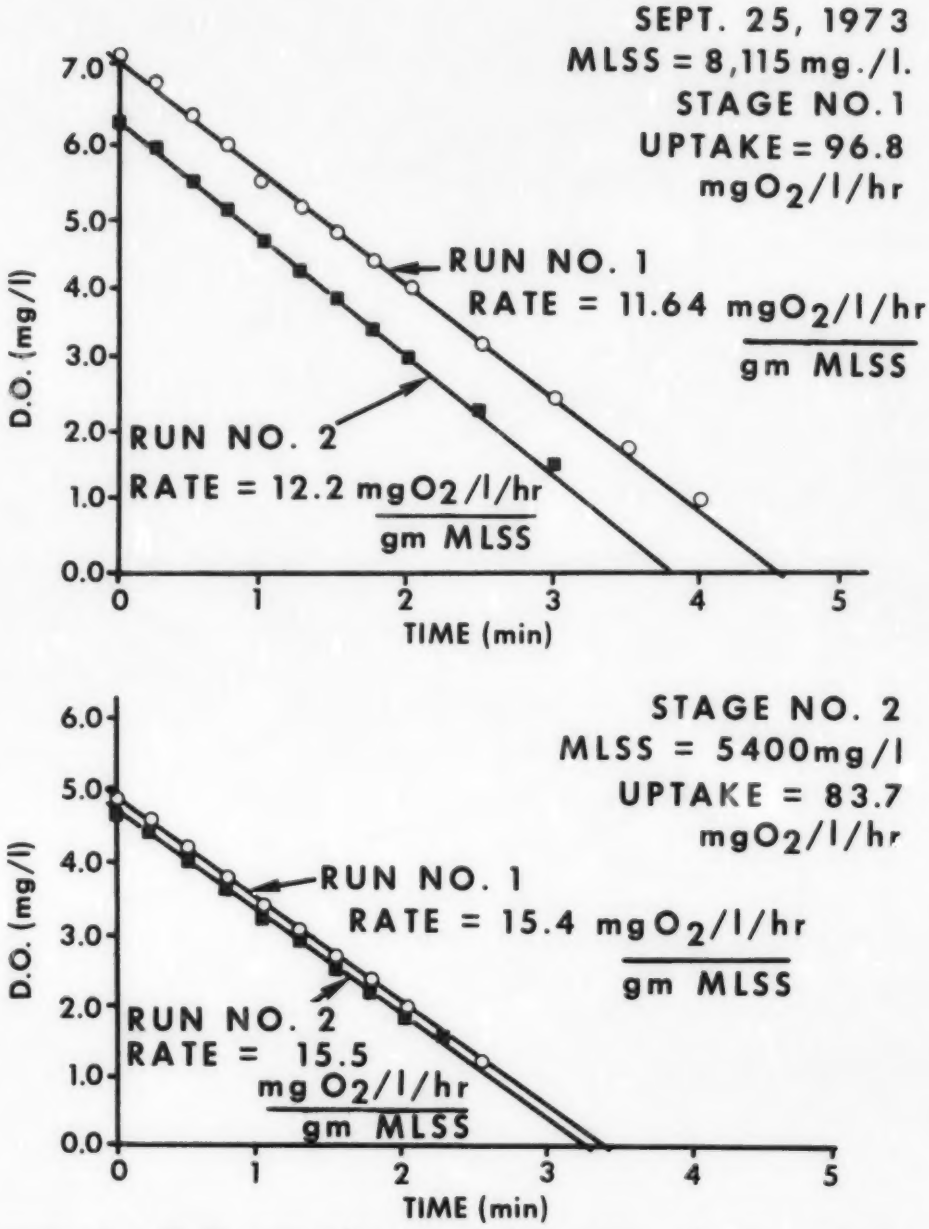

Figure 5. D.O. uptake as a function of time stage No. 1 and 2.

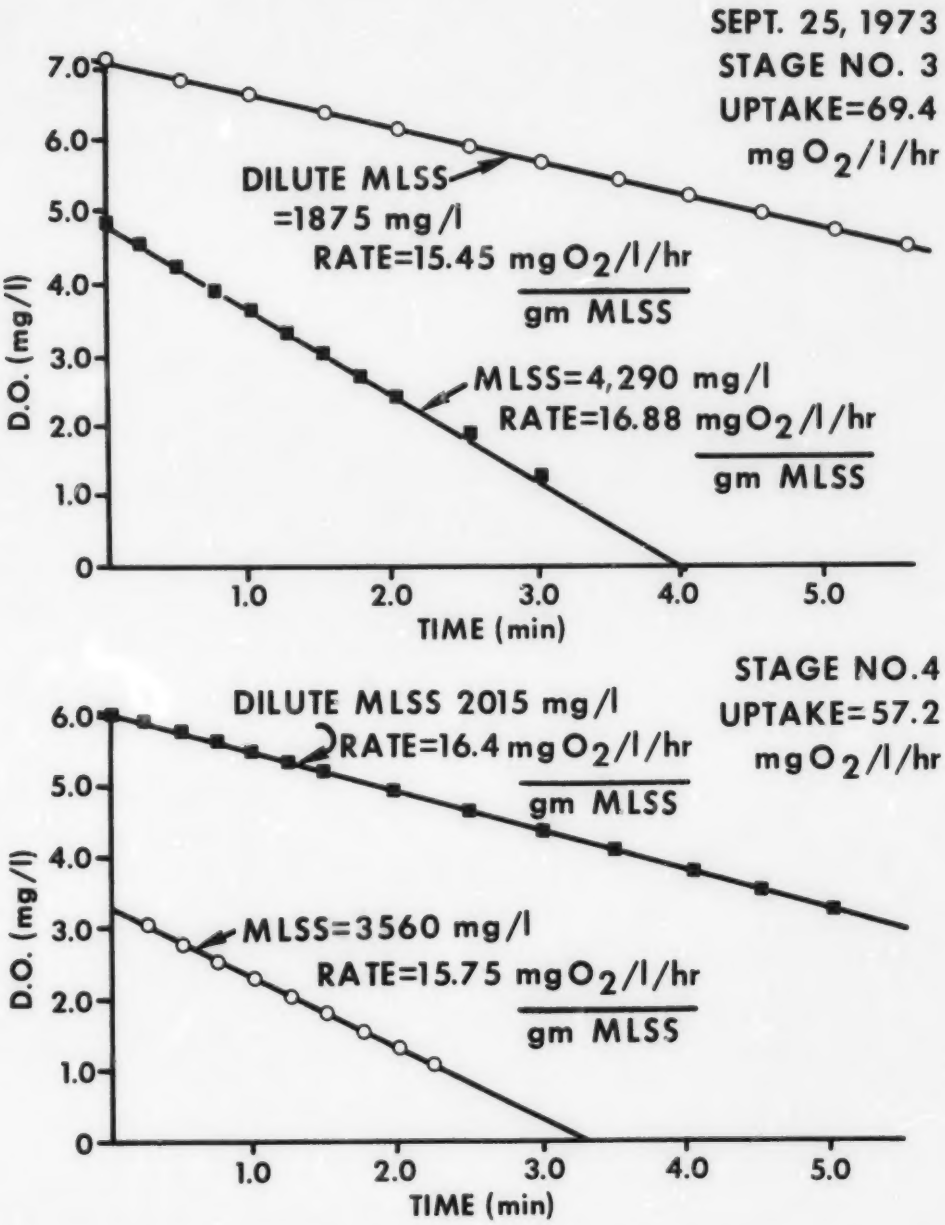

Figure 6. D.O. uptake as a function of time stage No. 3 and 4.

TABLE 10. STEP-FEED, O_2-ACTIVATED SLUDGE OXYGEN USAGE

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Time Period	O_2 In (kg)	O_2 Out (kg)	O_2 Usage (%)	O_2 D.O. Uptake (kg)	O_2 Usage (%)
Sept. 25[a]					
09:28-17:09	33.6	16.6	50	18.0	54
12:27-15:35	12.9	6.3	52	7.4	57
Sept. 27[b]					
10:03-18:24	49.0	25.6	48	21.1	44
15:10-18:24	21.2	11.4	54	8.5	40

[a] Average % O_2 in effluent gas 46%.
[b] Average % O_2 in effluent gas 49%.

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